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THE LOOK-POINT AIRCRAFT COORDINATE ESTIMATOR (LACE) AND POTENTIAL APPLICATIONS

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SUMMARY

A look-point aircraft coordinate estimator (LACE) consisting of a windshield runway symbol projector, pilot input controls, microprocessor, and eye-alignment device is described. The estimator is used by a pilot to determine his aircraft's position relative to a runway or other visible terrain or target. The pilot initially superimposes and then corrects the superposition of the runway symbol over the runway during approach during periods when the runway is visible. Using the pilot's inputs the microprocessor calculates the position of the aircraft in terms of runway coordinates, then generates an approach trajectory and issues instructions to an autopilot. The microprocessor contains a model of the aircraft's dynamics and calculates a theoretical aircraft trajectory. The theoretical position of the aircraft is then used to drive the runway symbol, with the pilot's input being additive. The system thus acts as an aid in making low visibility approaches and landings when only an occasional glimpse of the runway is possible and no ground referenced landing systems are available. The system can also be used as an independent landing monitor for ground referenced landing systems.

INTRODUCTION

There are two standard types of airplane instrument approaches to airports in use today, nonprecision and precision. Nonprecision approaches involve the use of ground referenced radio aids for lateral guidance, but rely on the altimeter for altitude guidance. Precision approaches use ground referenced radio aids for lateral and altitude guidance (glideslope). Both types of approaches require visual contact with the runway threshold, approach lights, or other suitable markings and require that the aircraft be in a position from which a normal approach to the runway can be made, in order to descend below certain minimum altitudes associated with each type of approach. In addition, if this visual contact is lost below these minimum altitudes a pull-up and go-around must be initiated immediately. Typically 61 meters for precision and 122 or more meters for nonprecision approaches are the minimum altitudes. The exception to this is the Category III-C precision approach which allows automatic landings with completely obscured visibility. There are no airports in the United States thus equipped however. Therefore, for most airplane approaches to airports the last one to three kilometers of the approach must be flown under visual conditions.

The purpose of this report is to introduce the concept of the look-point aircraft coordinate estimator (LACE) and to explain a possible system configuration for implementation. The intent of the LACE system is to allow safe flight below these minimum altitudes to be continued when visual contact is lost given that sufficient prior visual contact has occurred to initialize the system properly. The system is also intended for use at airports which have no ground referenced radio navigation aids, for use during night approaches under visual flight rules, and for use as an independent approach and landing progress and safety monitor for future Category III-C systems where an occasional glimpse of the runway is possible.

CONCEPT DESCRIPTION

The look-point aircraft coordinate estimator (LACE) shown in figure 1 is a concept for determining aircraft position relative to an outside reference (e.g., runway centerline) by using the pilot to superimpose a windshield projected symbol over the actual outside reference. An outboard computer then calculates the aircraft's position and heading relative to the runway using inputs to the windshield symbol projector and aircraft gyro and air data system information. The computer also generates an approach and landing trajectory and issues instructions to an autopilot. The LACE computer contains a mathematical model of the aircraft's dynamics by which a theoretical estimate of the actual aircraft trajectory is made. This estimate is used to drive the runway symbol, with the pilot's task being to correct any deviation observed. The pilot can only make these corrections when visual contact with the runway is possible.

The pilot maintains his head in a given position in the cockpit when using the eye elignment device shown in figure 1 and making corrections to the symbol's position. The pilot is aided in making visual contact with the runway by the windshield symbol which calls attention to that area most likely to contain the runway.

A possible choice for windshield projected symbols is shown in figure 2. The crossed-lines symbol represents the null position for the approach end of the runway centerline symbol. The null position must be adjusted so that it lies on an axis parallel to the airplane's longitudinal axis and passing through the pilot's eye. The pilot must be provided with appropriate visual cues that allow him to place his eye on this axis. The centerline symbol position is denoted by the variables $\varepsilon_{1,A}$, $\varepsilon_{2,A}$ and γ. The variable r is the distance from the pilot's eye to the windshield. An oculometer (reference 1) could also be used to measure the distances $r\varepsilon_{1,A}$ and $r\varepsilon_{2,A}$, and the angle γ.

Control of the windshield projected symbol is assumed effected by a strain measurement system on the control yoke and rudder pedals. Any separate controller, such as a side arm controller, control-yoke mounted controller, or combination, is a plausible alternative. A mechanical or electrical (for fly-by-wire systems) clutch for the yoke and rudder pedals which allows motion to be the control input for the windshield projected symbol is also possible. The autopilot would control the aircraft while the pilot is controlling the windshield projected symbol.

The lateral angle $\varepsilon_{1,A}$ is driven by measuring the rotational strain resulting from attempting to rotate the aileron control (clockwise for positive $\varepsilon_{1,A}$). This definition allows correct piloting sense since positive $\varepsilon_{1,A}$ denotes a desired change in flight path to the right and the airplane would then roll right. The pitch angle $\varepsilon_{2,A}$ is positioned primarily by fore and aft strain on the elevator control where aft strain yields positive $\varepsilon_{2,A}$. This also brings about a normal sense or feel of the airplane since positive $\varepsilon_{2,A}$ requires the pitch-up normally associated with aft motion of the elevator control. The rotation γ of the symbol can be made proportional to rudder pedal strain with right pedal yielding negative γ. There is a certain artificiality to this deflection since the rudder is normally used only for small yaw attitude changes. However, for the situation where the airplane is laterally displaced from a desired flight path, but roughly aligned with that flight path, the combined use of the controls normally associated with aileron and rudder is similar to that required to execute a sideslip maneuver towards the desired flight path, although the airplane will not execute this maneuver.

The runway centerline symbol could be flashed intermittently to alert the pilot to the fact that a safe approach and landing is not possible. This feature would be significant during situations when the aircraft has just broken out below the ceiling and the pilot gets his first glimpse of the runway and where the aircraft would have to bank excessively to align or would be too high or fast to touch down near the threshold.

MATHEMATICAL DEVELOPMENT

Two coordinate systems are illustrated in figure 3. The ground system (X_g, Y_g, Z_g) is fixed with respect to the Earth with the coordinate center at point A (designating the runway threshold and centerline intersection), the X-axis extending down the runway coincident with the runway centerline and the Z-axis vertical with positive Z downward. The point B is defined as the point on the extended centerline where the runway symbol's end is projected, given perfect superposition. The aircraft system (X_b, Y_b, Z_b) is fixed to the aircraft with conventional sense with ψ, θ, and ϕ being the Euler angles for successive Z-, Y-, and X-axis rotations of the aircraft with respect to the ground system. The point O is designated as the aircraft system center.

Using these definitions the following coordinate transformations can be written:

$$\begin{bmatrix} X_{A,b} \\ Y_{A,b} \\ Z_{A,b} \end{bmatrix} = E_{bg} \begin{bmatrix} X_{A,g} - X_{o,g} \\ Y_{A,g} - Y_{o,g} \\ Z_{A,g} - Z_{o,g} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} X_{B,b} \\ Y_{B,b} \\ Z_{B,b} \end{bmatrix} = E_{bg} \begin{bmatrix} X_{B,g} - X_{o,g} \\ Y_{B,g} - Y_{o,g} \\ Z_{B,g} - Z_{o,g} \end{bmatrix} \tag{2}$$

where

$$E_{bg} = \begin{bmatrix} C_\theta C_\psi & C_\theta S_\psi & -S_\theta \\ -C_\phi S_\psi + S_\phi S_\theta C_\psi & C_\phi C_\psi + S_\phi S_\theta S_\psi & S_\phi C_\theta \\ S_\phi S_\psi + C_\phi S_\theta C_\psi & -S_\phi C_\psi + C_\phi S_\theta S_\psi & C_\phi C_\theta \end{bmatrix} \tag{3}$$

($C_{(v)}$ is shorthand notation for cos (v); $S_{(v)}$ for sin (v))

and

$$\begin{bmatrix} X_{A,g} \\ Y_{A,g} \\ Z_{A,g} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \text{ and } \begin{bmatrix} X_{B,g} \\ Y_{B,g} \\ Z_{B,g} \end{bmatrix} = \begin{bmatrix} X_{B,g} \\ 0 \\ 0 \end{bmatrix} \tag{4}$$

Making the assumption that the look axis for points A and B and the aircraft axis X_b are nearly coincident except for the small angles ε the following can be written:

$$\begin{bmatrix} X_{A,b} \\ Y_{A,b} \\ Z_{A,b} \end{bmatrix} = \begin{bmatrix} R_A \\ R_A \varepsilon_{1,A} \\ -R_A \varepsilon_{2,A} \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} X_{B,b} \\ Y_{B,b} \\ Z_{B,b} \end{bmatrix} = \begin{bmatrix} R_B \\ R_B \varepsilon_{1,B} \\ -R_B \varepsilon_{2,B} \end{bmatrix} \tag{5}$$

Substituting equations (3), (4), and (5) into (1) and (2), combining (1) and (2), and expanding yields.

$$R_B = R_A + X_{B,g}\, C_\theta C_\psi \tag{6}$$

$$\varepsilon_{1,B} R_B = \varepsilon_{1,A} R_A + X_{B,g}\, (-C_\phi S_\psi + S_\phi S_\theta C_\psi) \tag{7}$$

$$-\varepsilon_{2,B} R_B = -\varepsilon_{2,A} R_A + X_{B,g}\, (S_\phi S_\psi + C_\phi S_\theta C_\psi) \tag{8}$$

There are four unknowns in the above three equations. However, a straight forward manipulation will yield equations defining the relative heading ψ.

$$S_\psi = \sin\psi = \frac{R_A}{X_{B,g}} \frac{f_S}{f_D}; \quad C_\psi = \cos\psi = \frac{R_A}{X_{B,g}} \frac{f_C}{f_D} \tag{9}$$

where

$$f_S = \left[\varepsilon_{2,B} - \varepsilon_{2,A}\right] \left[(S_\phi - T_\gamma C_\phi)\, S_\theta - (\varepsilon_{1,B} + T_\gamma \varepsilon_{2,B}) C_\theta\right]$$

$$f_C = \left[\varepsilon_{2,B} - \varepsilon_{2,A}\right] \left[T_\gamma S_\phi + C_\phi\right]$$

$$f_D = -S_\theta + (\varepsilon_{1,B}\, S_\phi - \varepsilon_{2,B}\, C_\phi) C_\theta$$

By defining ψ_o by the equation

$$\tan \psi_o = \frac{S_\phi - T_\gamma C_\phi}{C_\phi + T_\gamma S_\phi} S_\theta - \frac{\varepsilon_{1,B} + T_\gamma \varepsilon_{2,B}}{C_\phi + T_\gamma S_\phi} C_\theta \qquad (10)$$

where $T_\gamma = \tan \gamma = - \dfrac{\varepsilon_{1,B} - \varepsilon_{1,A}}{\varepsilon_{2,B} - \varepsilon_{2,A}}$

ψ can be determined as follows

$$\psi = \psi_o \quad \text{if } S_\psi \geq 0 \text{ and } C_\psi \geq 0$$

$$\psi = 180^\circ + \psi_o \text{ if } C_\psi < 0 \qquad (11)$$

$$\psi = 360^\circ + \psi_o \text{ if } S_\psi < 0 \text{ and } C_\psi \geq 0$$

It is noted that all the variables in equations (9, 10, 11) are measured onboard the aircraft.

Substituting equations (4) and (5) into (1) and noting that because of orthogonality $E_{bg}^{-1} = E_{bg}^{T}$ the following can be written:

$$\frac{X_{o,g}}{R_A} = -C_\theta C_\psi - \varepsilon_{1,A}(-C_\phi S_\psi + S_\phi S_\theta C_\psi) + \varepsilon_{2,A}(S_\phi S_\psi + C_\phi S_\theta C_\psi) \qquad (12)$$

$$\frac{Y_{o,g}}{R_A} = -C_\theta S_\psi - \varepsilon_{1,A}(C_\phi C_\psi + S_\phi S_\theta S_\psi) + \varepsilon_{2,A}(-S_\phi C_\psi + C_\phi S_\theta S_\psi) \qquad (13)$$

$$\frac{Z_{o,g}}{R_A} = S_\theta - \varepsilon_{1,A} S_\phi C_\theta + \varepsilon_{2,A} C_\phi C_\theta \qquad (14)$$

Since the relative aircraft heading ψ has been determined, these equations contain only the desired aircraft coordinates and the range R_A. Since the aircraft's altitude is known, $Z_{o,g}$ could be computed (given the runway elevation), and the other coordinates calculated. Radar altimeter data could also be used. However, examination of equation (14) shows that for low relative altitudes the calculation of range R_A is sensitive to measurement errors in the angles θ and $\varepsilon_{2,A}$.

A second method to calculate range involves differentiating equations (12) and (13) with respect to time and then with approximate knowledge of aircraft velocity from air data, (introducing an error varying with wind velocity), relative heading, and numerical derivatives of the right-hand-sides of equations (12) and (13) the range can be calculated as follows:

$$\dot{X}_{o,g} = R_A \dot{f}_1 + \dot{R}_A f_1 \tag{12a}$$

$$\dot{Y}_{o,g} = R_A \dot{f}_2 + \dot{R}_A f_2 \tag{13a}$$

where f_1 and f_2 are the expressions on the right-hand-sides of equations (12) and (13), and $\dot{f}_1$ and $\dot{f}_2$ are time derivatives of f_1 and f_2.

Therefore

$$R_A = \frac{f_2 \dot{X}_{o,g} - f_1 \dot{Y}_{o,g}}{\dot{f}_1 f_2 - \dot{f}_2 f_1} \tag{15}$$

From equation (15) it can be seen the range R_A cannot be determined when $\dot{f}_1 f_2 - \dot{f}_2 f_1 = 0$. To gain insight into this problem, assume the airplane is flying straight and level $(\phi = \theta = 0)$. In this case equation (15) reduces to

$$R_A = \frac{\dot{X}_{o,g}\, S(\psi + \varepsilon_{1,A}) - \dot{Y}_{o,g}\, C(\psi + \varepsilon_{1,A})}{\dot{\psi} + \dot{\varepsilon}_{1,A}} \tag{16}$$

This expression can be understood by referring to figure 3. The indeterminate condition is seen to occur when the aircraft is flying directly towards point A, in which case $\dot{\psi} + \dot{\varepsilon}_{1,A} = 0$.

A third method to calculate the range R_A is to use an estimation filter (such as a Kalman filter), wherein the airplane dynamics and equations (12), (12a), (13), (13a), and (14) form the plant model. The advantage of this method lies in the fact that the equations describing the airplane dynamics are additional informations not utilized in the first two methods, which allow the prediction of range based on time history data rather than data at the present instant only. Wind speed and direction can also be estimated allowing better wind shear and cross wind corrections during approach and landing.

CONCEPT IMPLEMENTATION

A block diagram for the LACE system is given in figure 5. The pilot initially aligns the runway centerline symbol and the runway and then closes switch SA for a short period of time. During this time algorithms are solved which determine aircraft position and heading relative to the runway. These algorithms require knowledge of aircraft state variable estimates of roll ϕ_e, pitch θ_e, airspeed V_e, and altitude $h_{o,e}$, as well as the runway elevation $h_{A,g}$ and estimates of the wind speed V_{ω_e} and direction ψ_{ω_e}. These inputs allow R_A to be estimated by two different techniques. A selection algorithm would examine these two estimates for numerical consistency. Knowledge of the wind could be determined onboard using aircraft drift measurements or could be estimated from weather data and entered into the LACE computer prior to the approach.

When the pilot opens switch SA, the aircraft coordinates at that time t_o are used to calculate an optimum flight path to the runway. Simultaneously a mathematical model of the aircraft using roll, pitch, airspeed, and wind estimates is solved allowing an open loop estimate of aircraft position. The difference between these two positions is fed to a steering law which then determines desired aircraft heading, airspeed, and altitude for autopilot input.

The aircraft's position estimate is also used to determine runway centerline symbol location on the windshield for overlap of the actual runway. This feature would aid the pilot in finding the runway once the system had been initialized and the aircraft was in and out of weather during the approach. Switch B is therefore closed after time t_o.

CONCLUDING REMARKS

This report has presented a concept for using pilot look-point to determine the position of an aircraft relative to a runway or other visible terrain or target. The report also contains a suggested method of implementing the concept which allows the conduct of an evaluation. The report has presented some potential problem areas associated with inexact measurements and with certain relative alignments of the aircraft and runway.

It is felt that the system has the potential of offering the pilot of an aircraft an important aid in making landings at an airport under conditions where only intermittent glimpses of the runway are possible. Also, once initialized the runway symbol could be an important aid by calling attention to the area of the windshield where the runway is most likely to be seen. The system also allows the use of optimum trajectories to the runway, from the identified position, in clear weather as well as poor weather.

Also, while visible terrain or features outside the aircraft (runway) have been discussed the features need not be visible if some aid such as an infrared or radar presentation of the reference is available to the pilot instead, with the symbol presentation and motion control being now associated with the presentation device.

Finally, it is possible to substitute a device, such as an oculometer, which measures pilot look-point directly, for the windshield symbol, and thus simplify the operational use of the device.

REFERENCE

Middleton, D. B.; Hurt, G. J.; Wise, M. A.; and Holt, J. D.: Description and Flight Tests of an Oculometer. TN D-8419, January 1977.

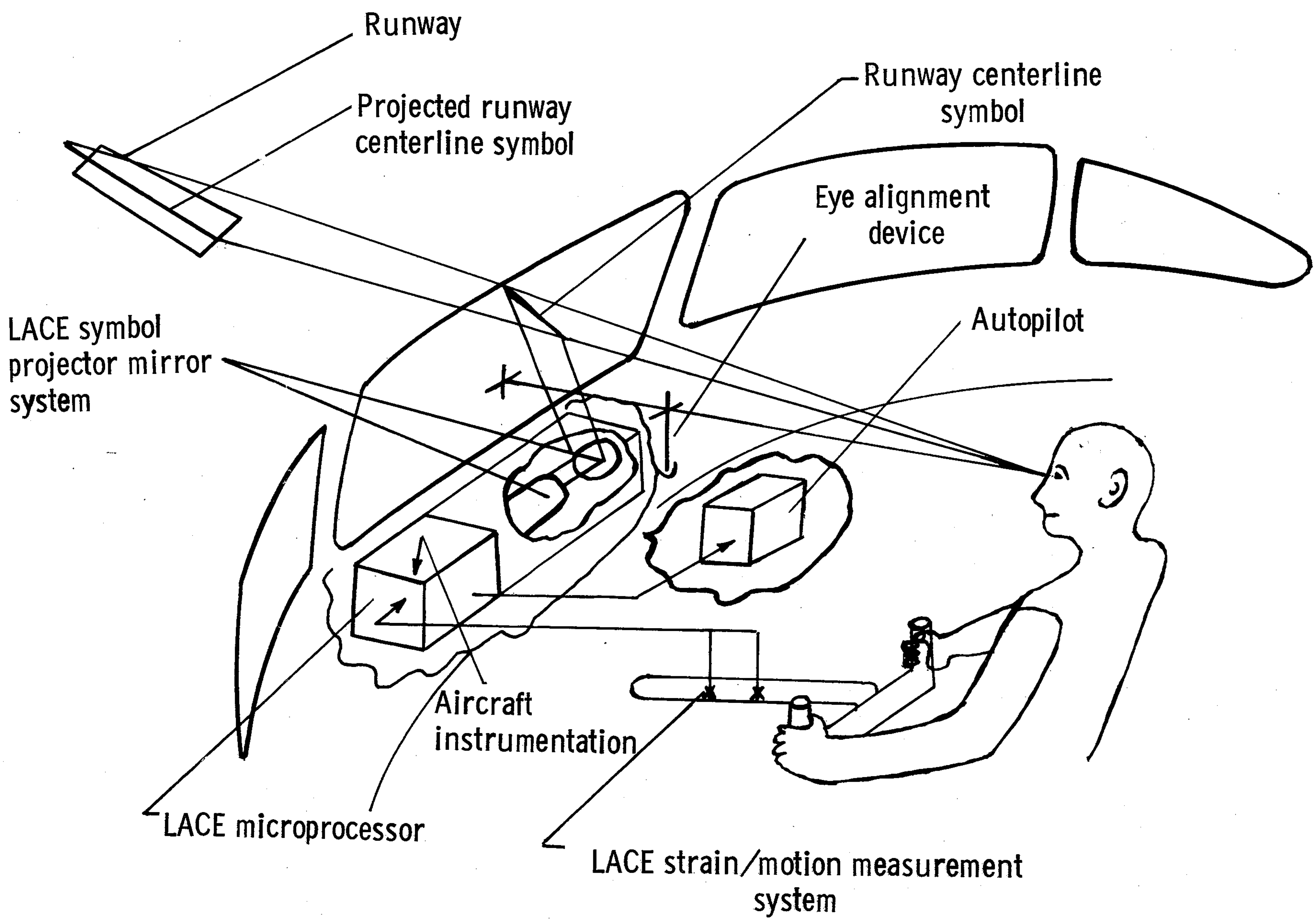

Figure 1.- LACE system.

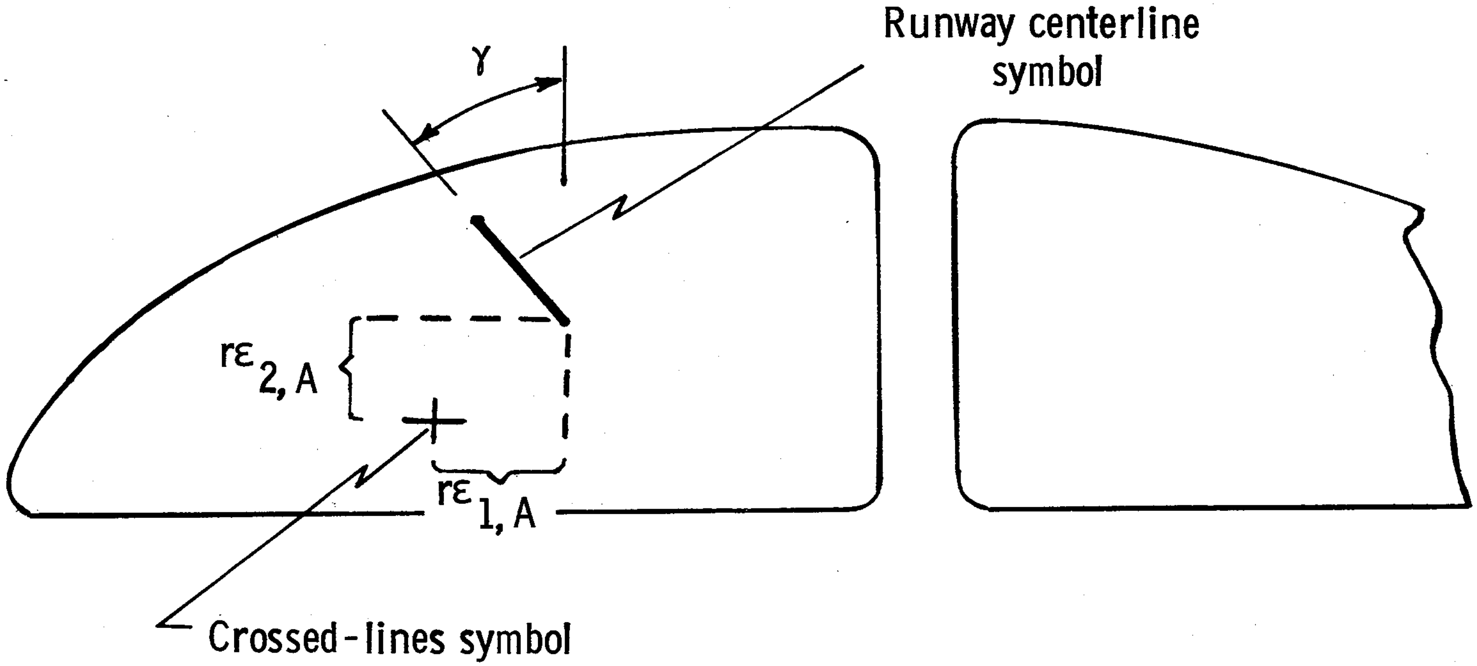

Figure 2.- LACE windshield symbology

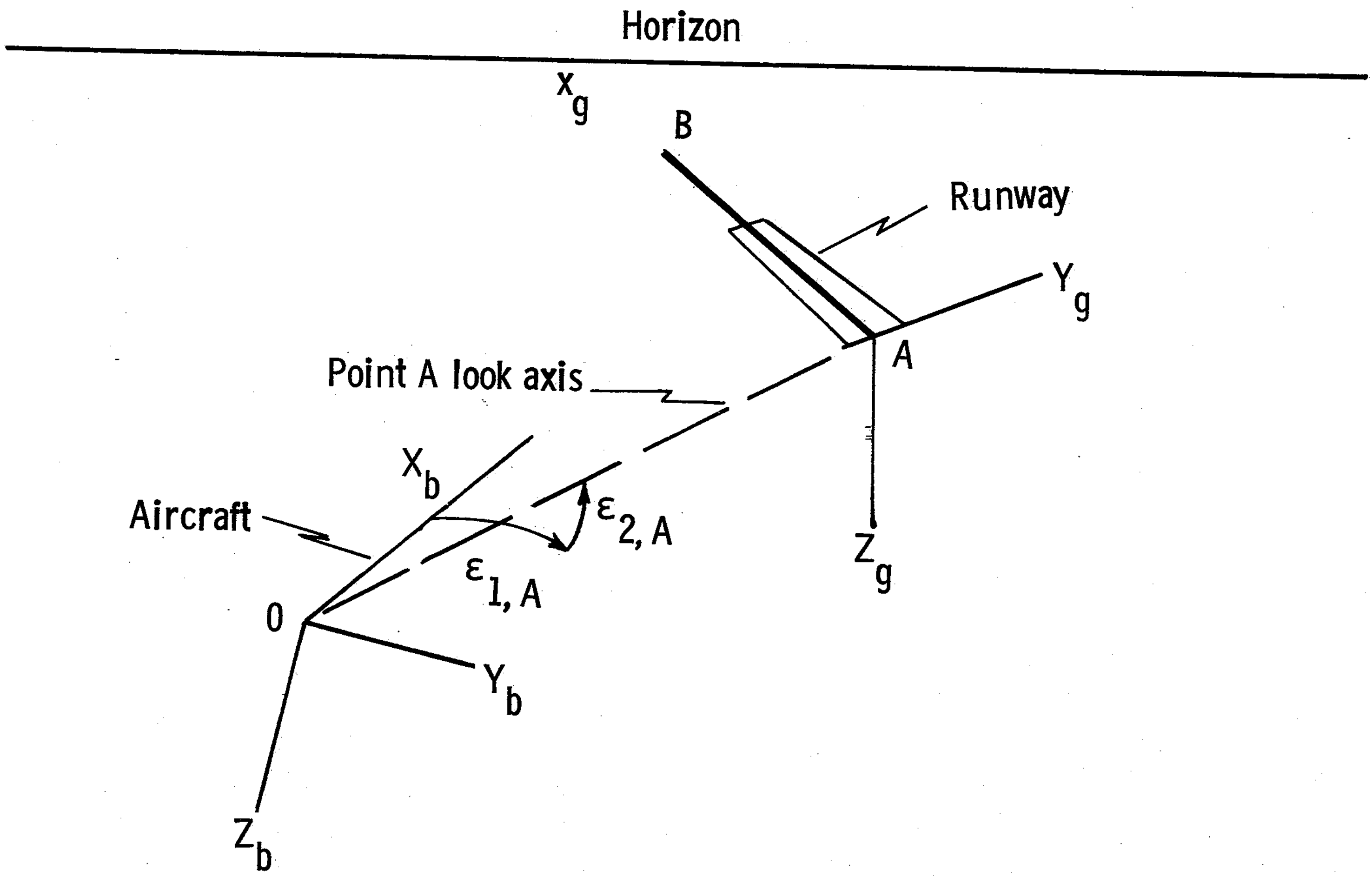

Figure 3.- Coordinate system definitions.

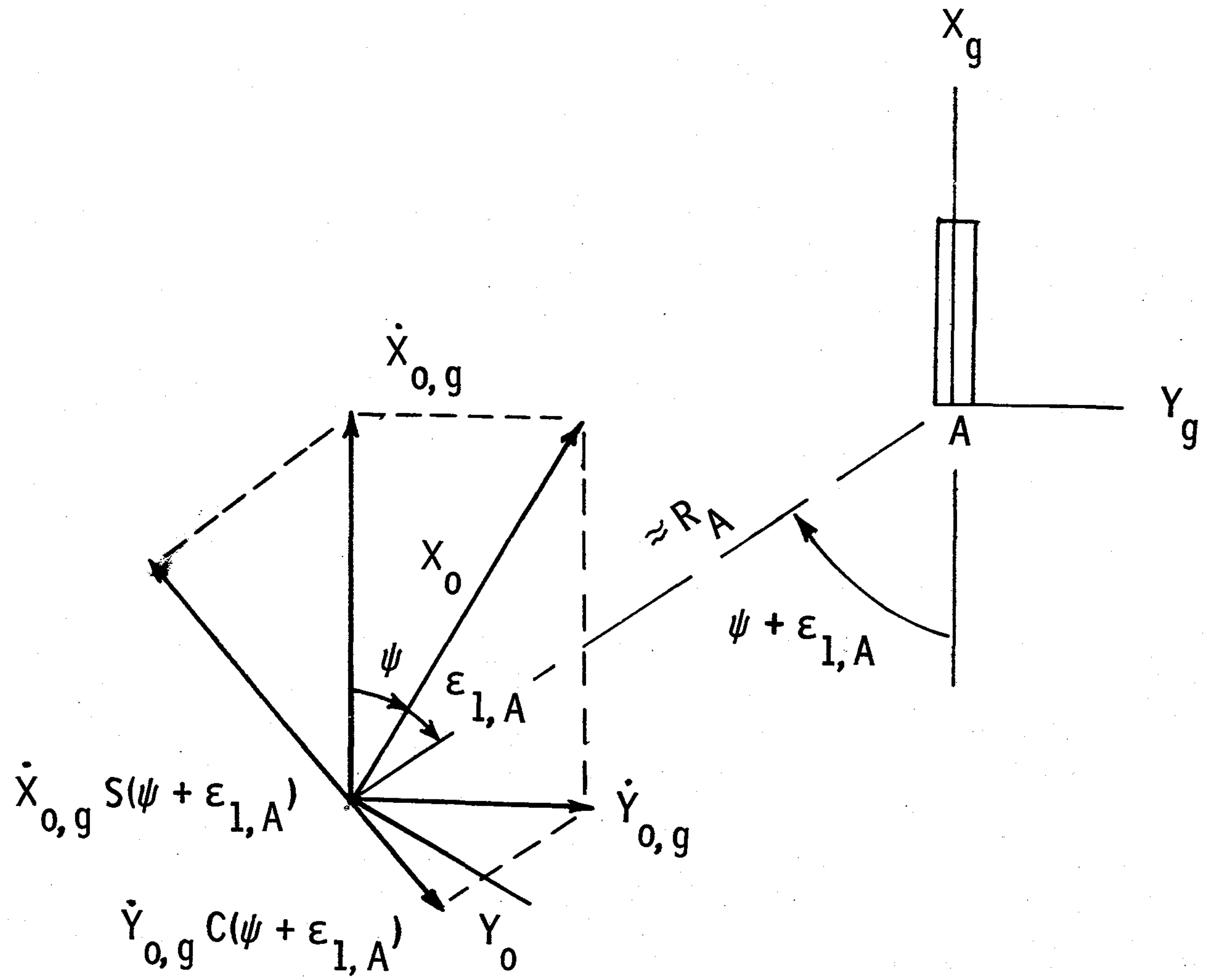

Figure 4.- Velocity vectors for $\theta = 0$, $\phi = 0$ case.

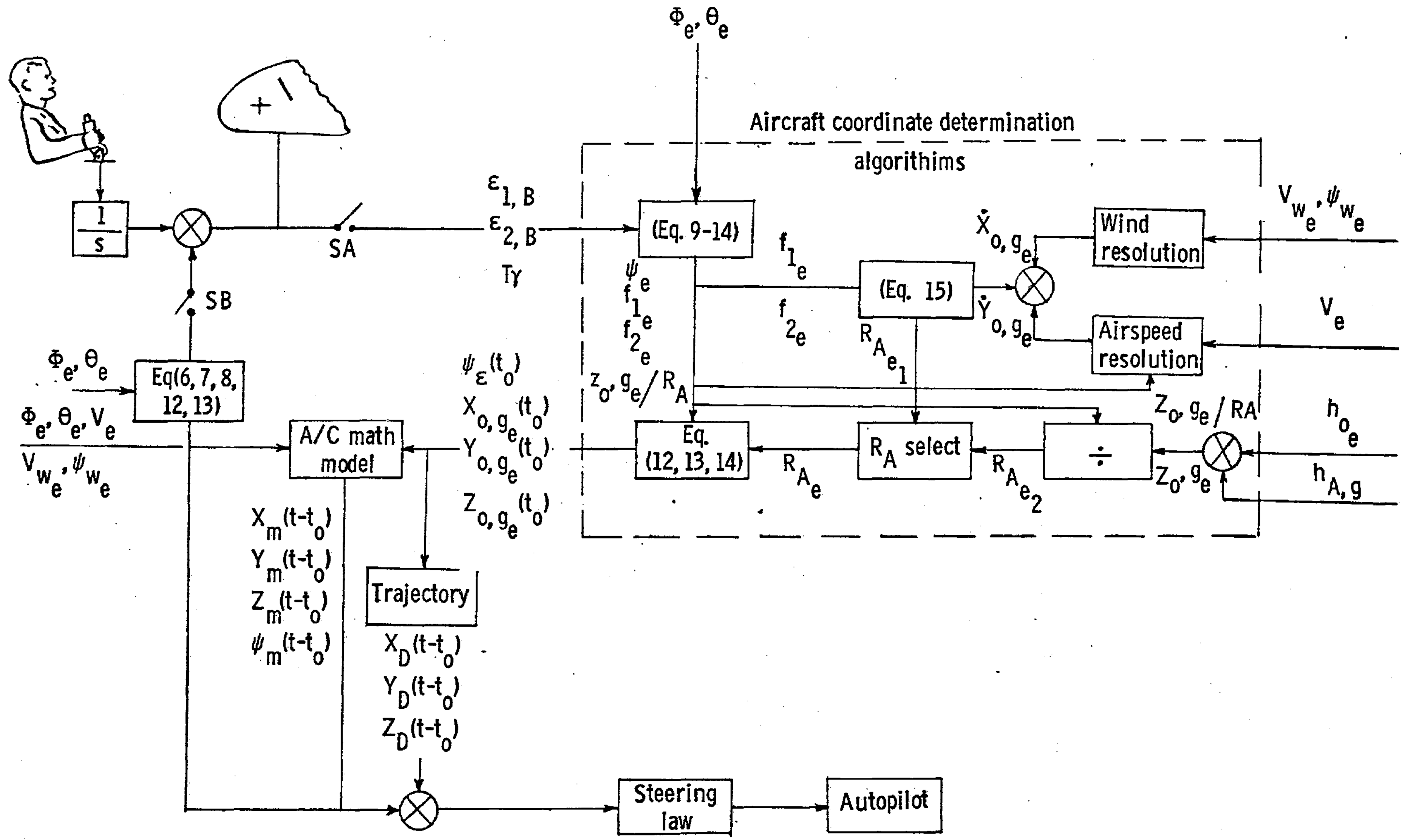

Figure 5.- LACE block diagram.

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16. Abstract

A look-point aircraft coordinate estimator (LACE) consisting of a windshield runway symbol projector, pilot input controls, microprocessor, and eye-alignment device is described. The estimator is used by a pilot to determine his aircraft's position relative to a runway or other visible terrain or target. The pilot initially superimposes and then corrects the superposition of the runway symbol over the runway during approach during periods when the runway is visible. Using the pilot's inputs the microprocessor calculates the position of the aircraft in terms of runway coordinates, then generates an approach trajectory and issues instructions to an autopilot. The microprocessor contains a model of the aircraft's dynamics and calculates a theoretical aircraft trajectory. The theoretical position of the aircraft is then used to drive the runway symbol, with the pilot's input being additive. The system thus acts as an aid in making low visibility approaches and landings when only an occasional glimpse of the runway is possible and no ground referenced landing systems are available. The system can also be used as an independent landing monitor for ground referenced landing systems.

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